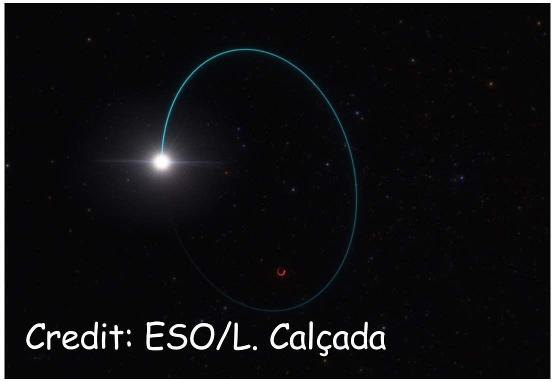
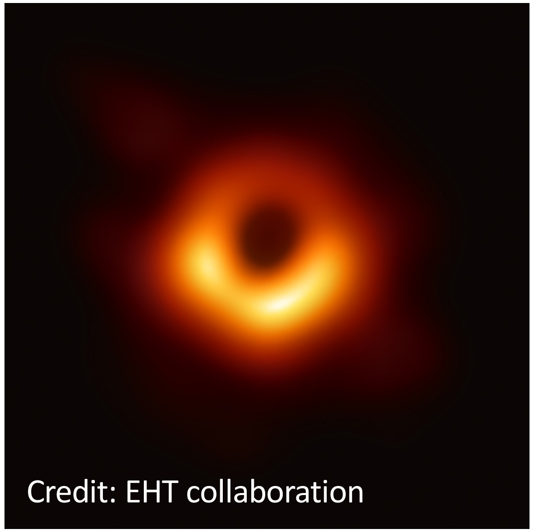
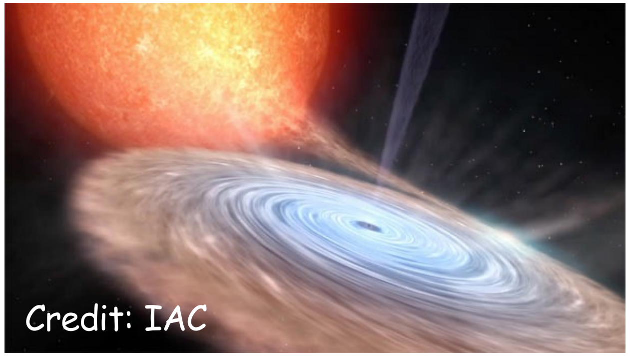
Spectral properties of accreting black holes and neutron stars in X-ray binaries

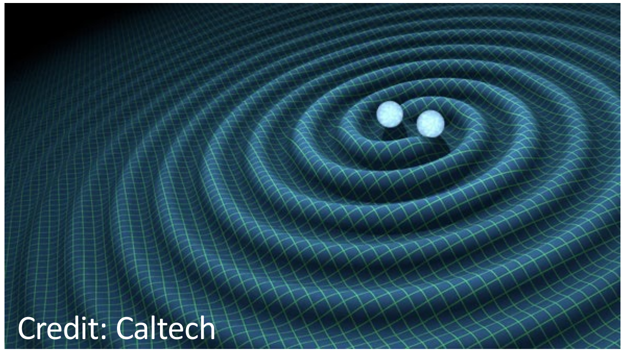
Black hole flavours

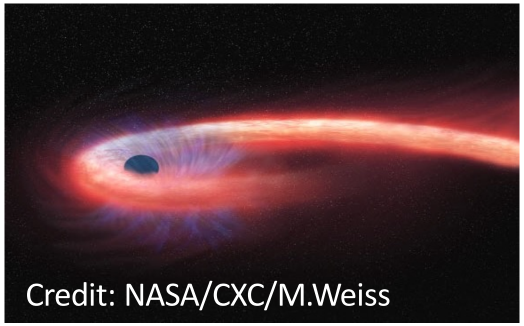


- Black hole has only 2 parameters: **mass and spin**
- Observational appearance depends on these parameters

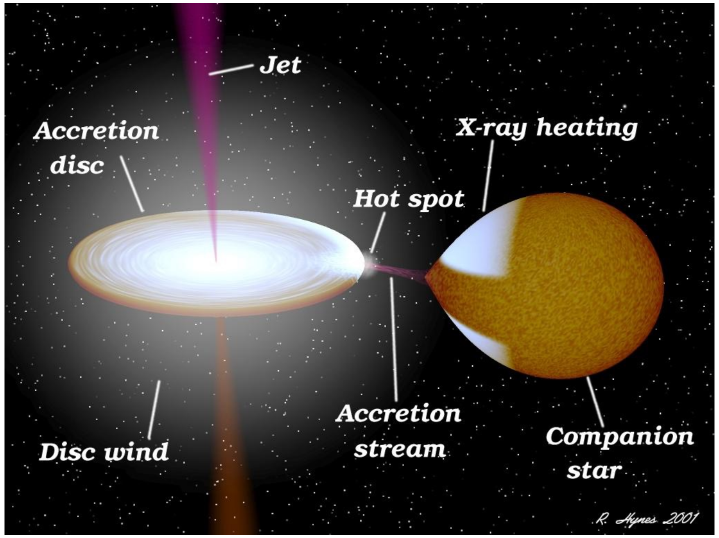








X-ray binaries



$L_X \sim 10^{35}$-10^{39} erg/s

- HMXB: wind
- LMXB: Roche lobe overflow

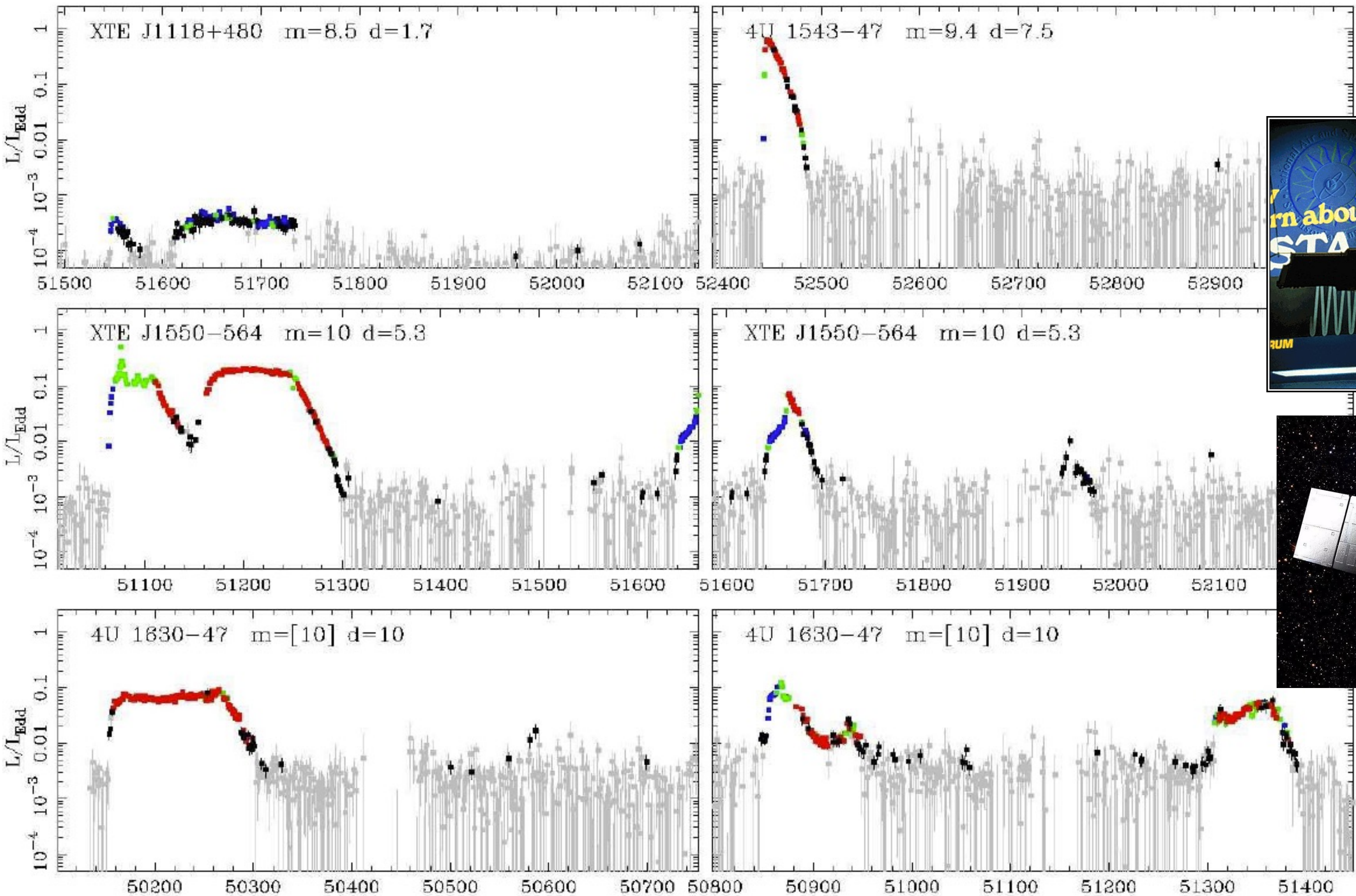
Radio, IR, optical, UV:

- outflows, jets
- donor star
- outer accretion disk
- hot accretion flow

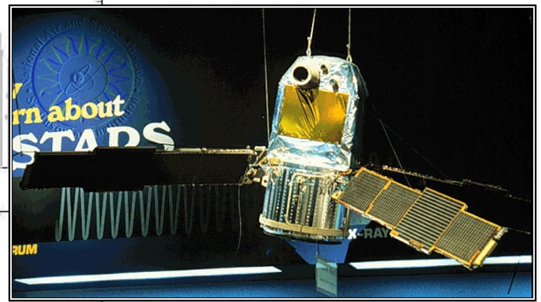
X/γ-ray emission:

- hot accretion flow
- cold accretion disk
- neutron star surface/boundary layer
- outflows, jets ???

BH outbursts



Uhuru



Rossi X-ray Timing Explorer

BH outbursts

- Differential photon number:

$\mathrm{d}N/\mathrm{d}E = N_0\, E^{-\Gamma}$ [photons / s / keV], power law

  - photon index Γ

- Differential flux:

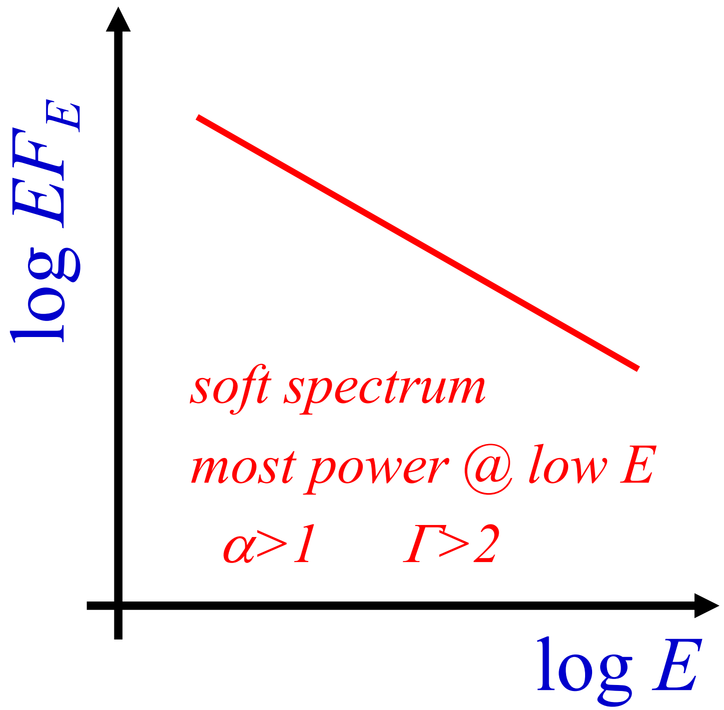
$E\, \mathrm{d}N/\mathrm{d}E = \mathrm{d}F/\mathrm{d}E = F_E = F_0\, E^{-\alpha}$ [energy / s / keV]

  - energy index $\alpha = \Gamma - 1$

- Differential energy distribution:

$E^2\, \mathrm{d}N/\mathrm{d}E = EF_E = \nu F_\nu$

- Plot EF_E peaks at energy where power output of source peaks



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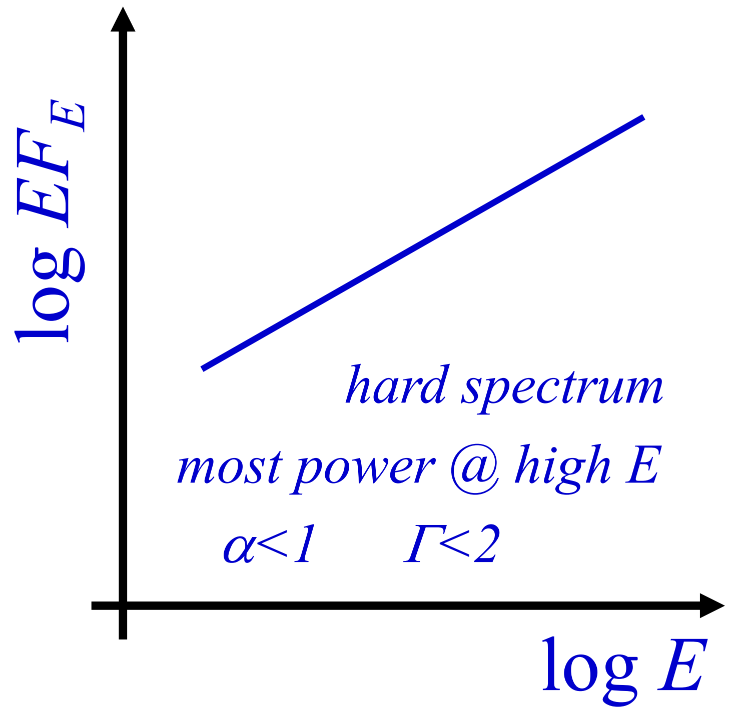

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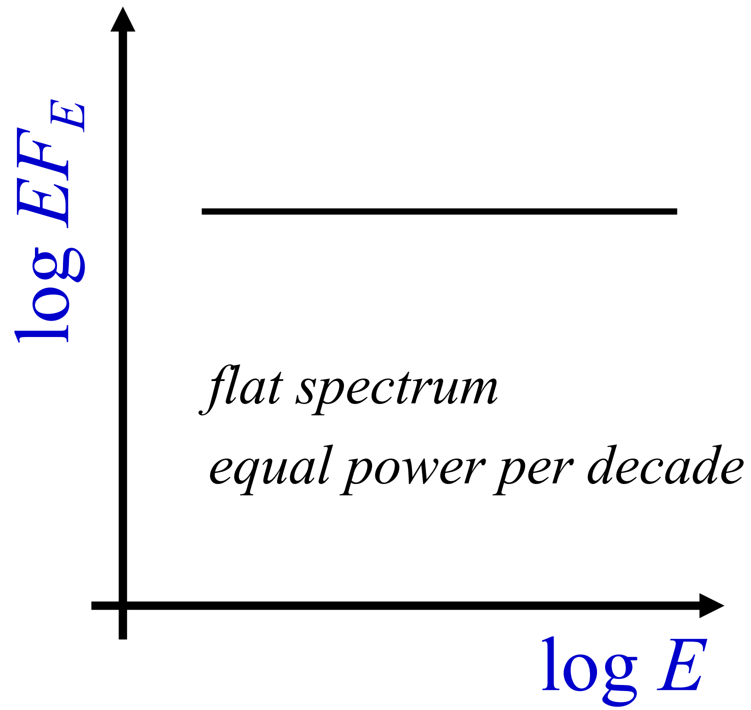
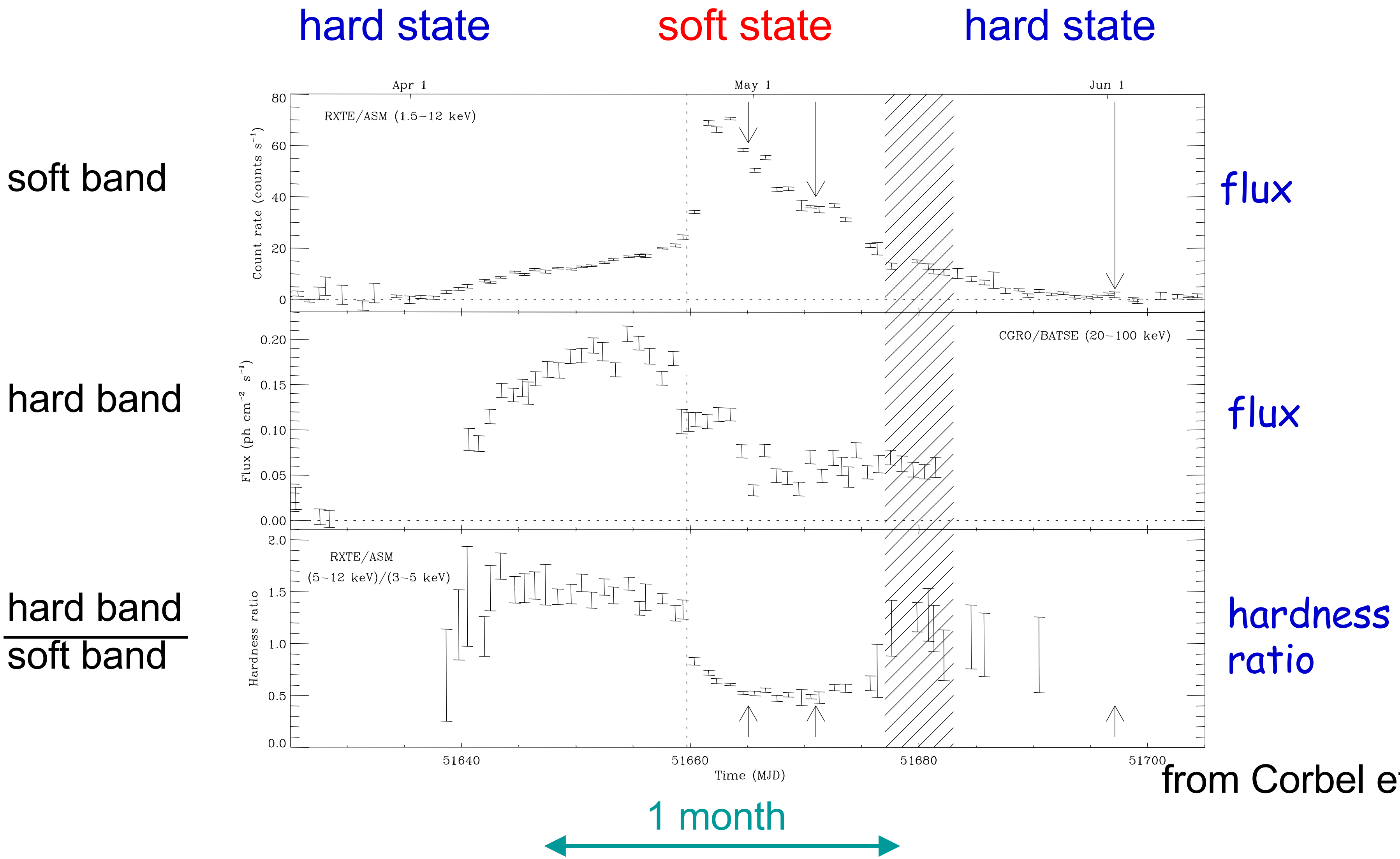
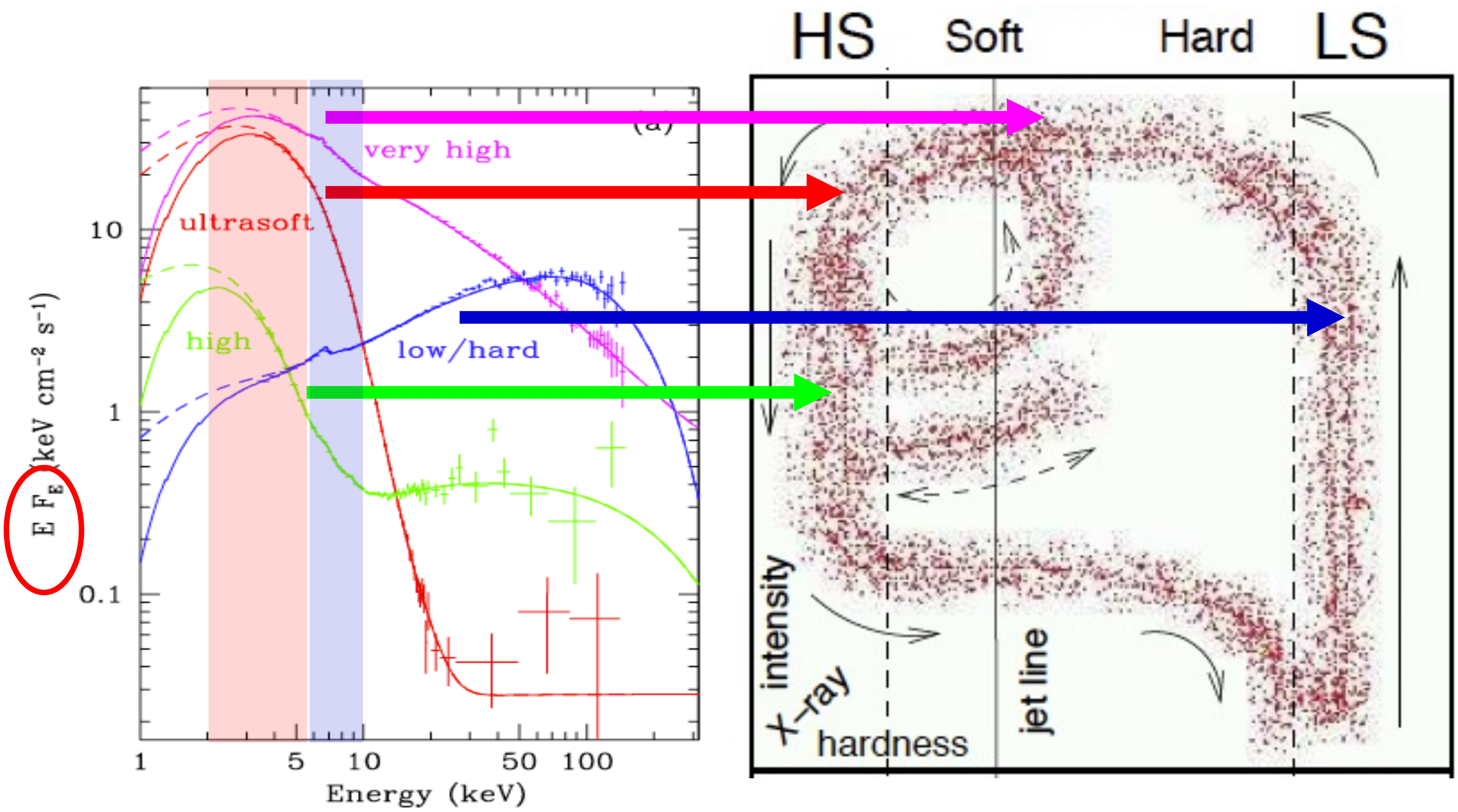


BH outbursts

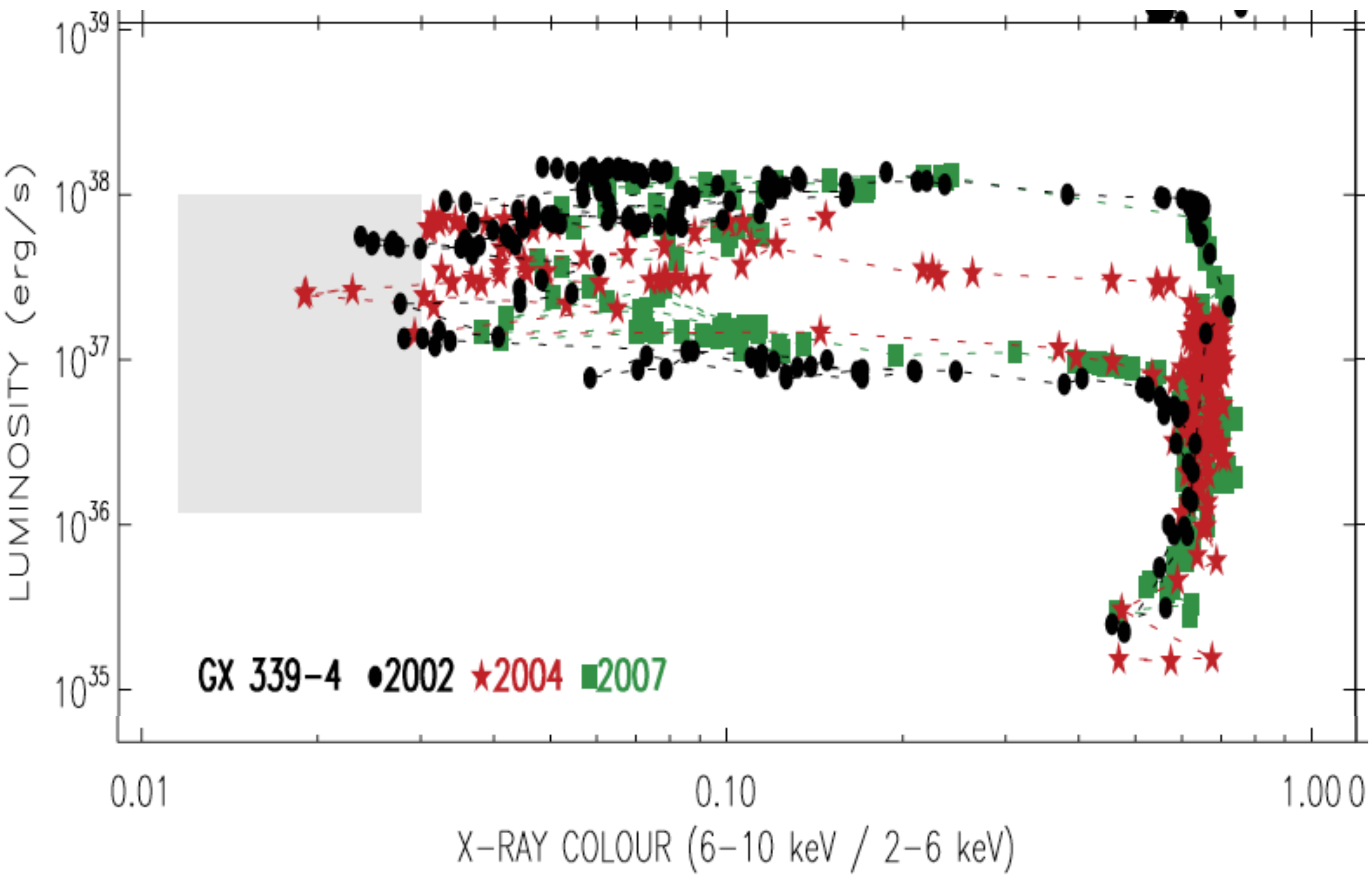


from Corbel et al.

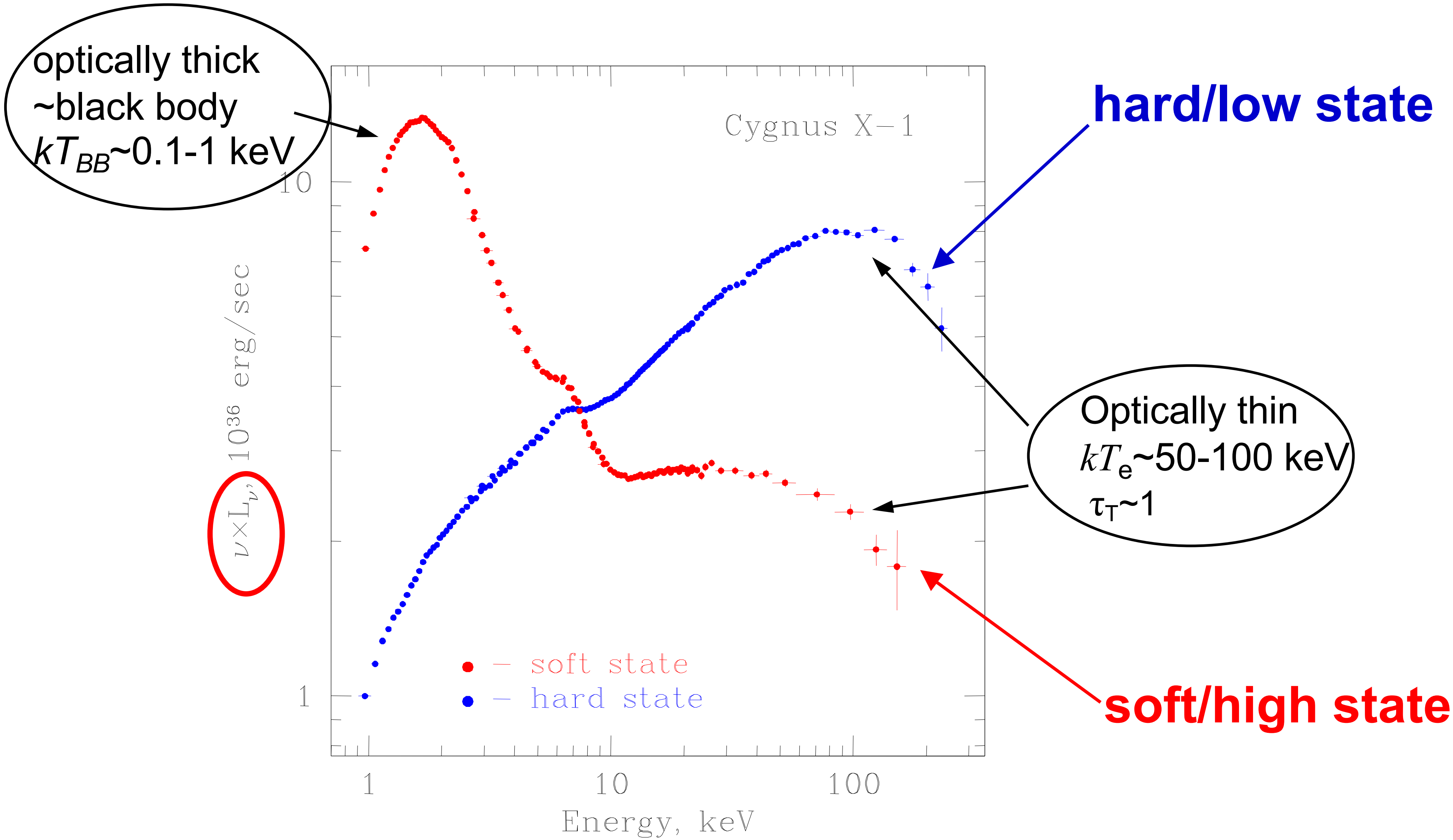
BH outbursts



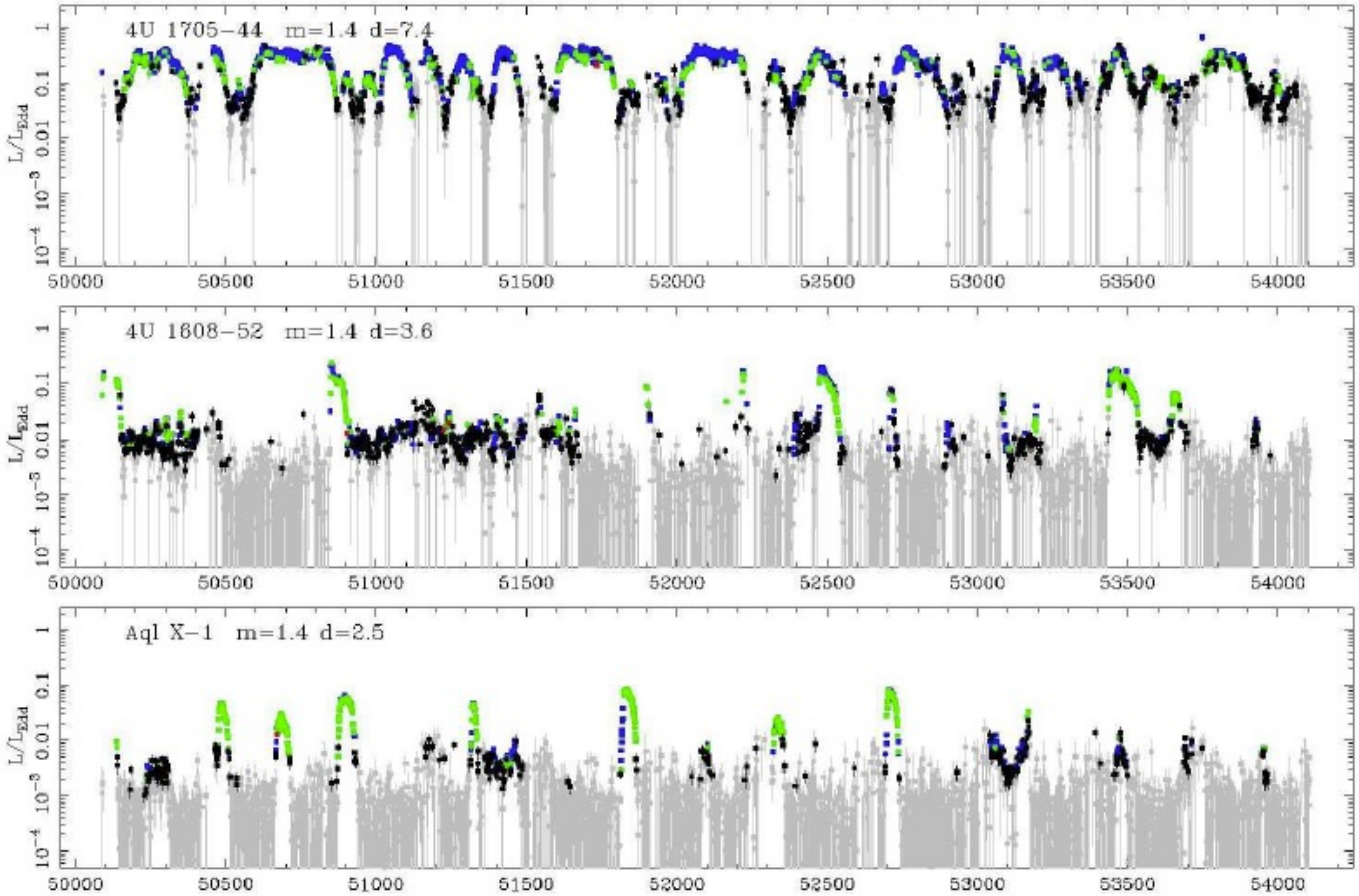
BH outbursts



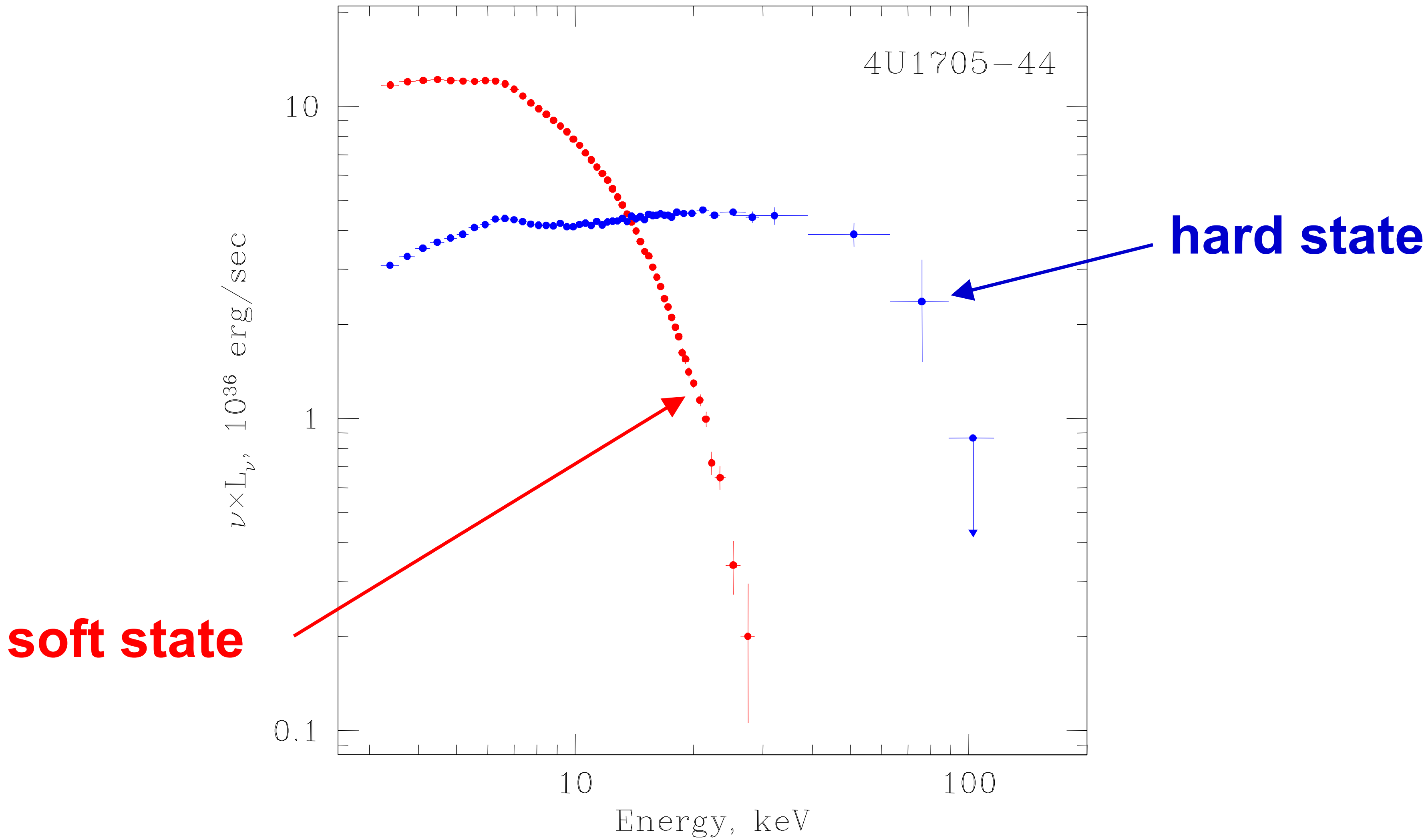
BH spectral states:
optically **thick** and **thin** emission



NS X-ray binaries



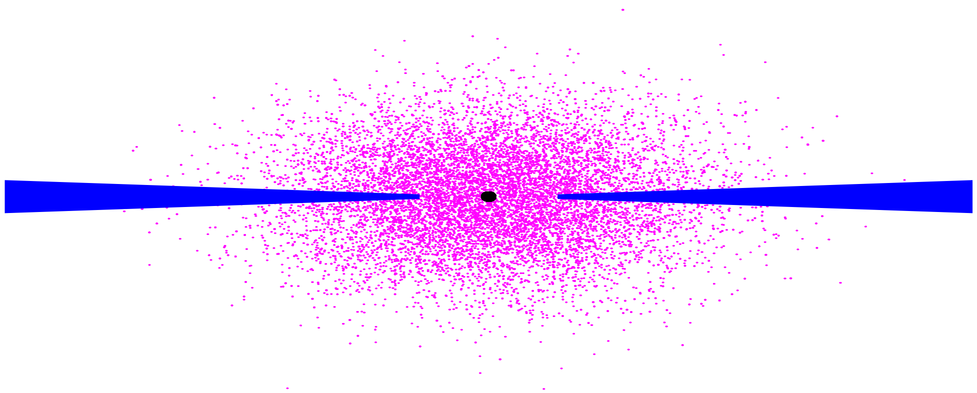
NS spectral states

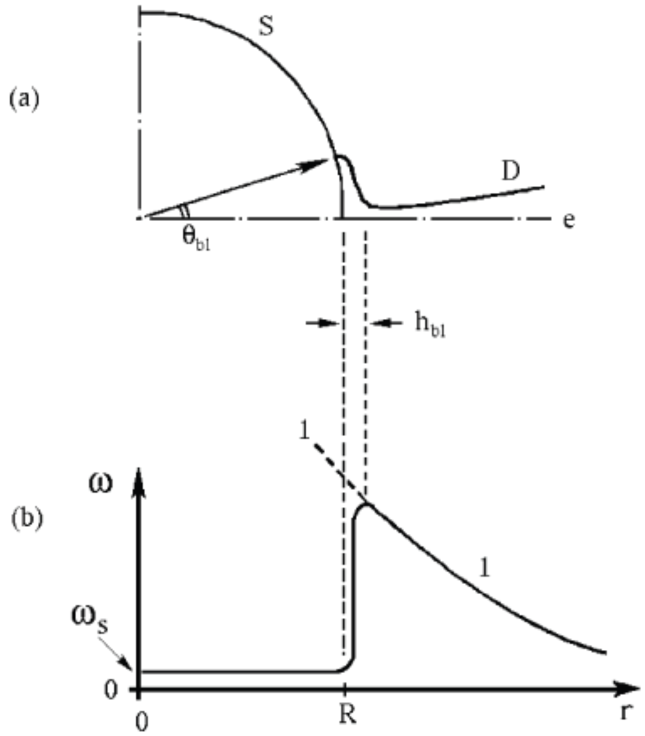


BH & NS

	BH	**NS**
size		
$R_{disk} \sim 3R_S \sim M$	~100 km	~10 km
time scales		
$t_K \sim M$	~10 msec	~1 msec
hard surface	**NO**	**YES**

BH | **NS**





Sunyaev & Shakura, 1986
Inogamov & Sunyaev, 1999

NO boundary layer

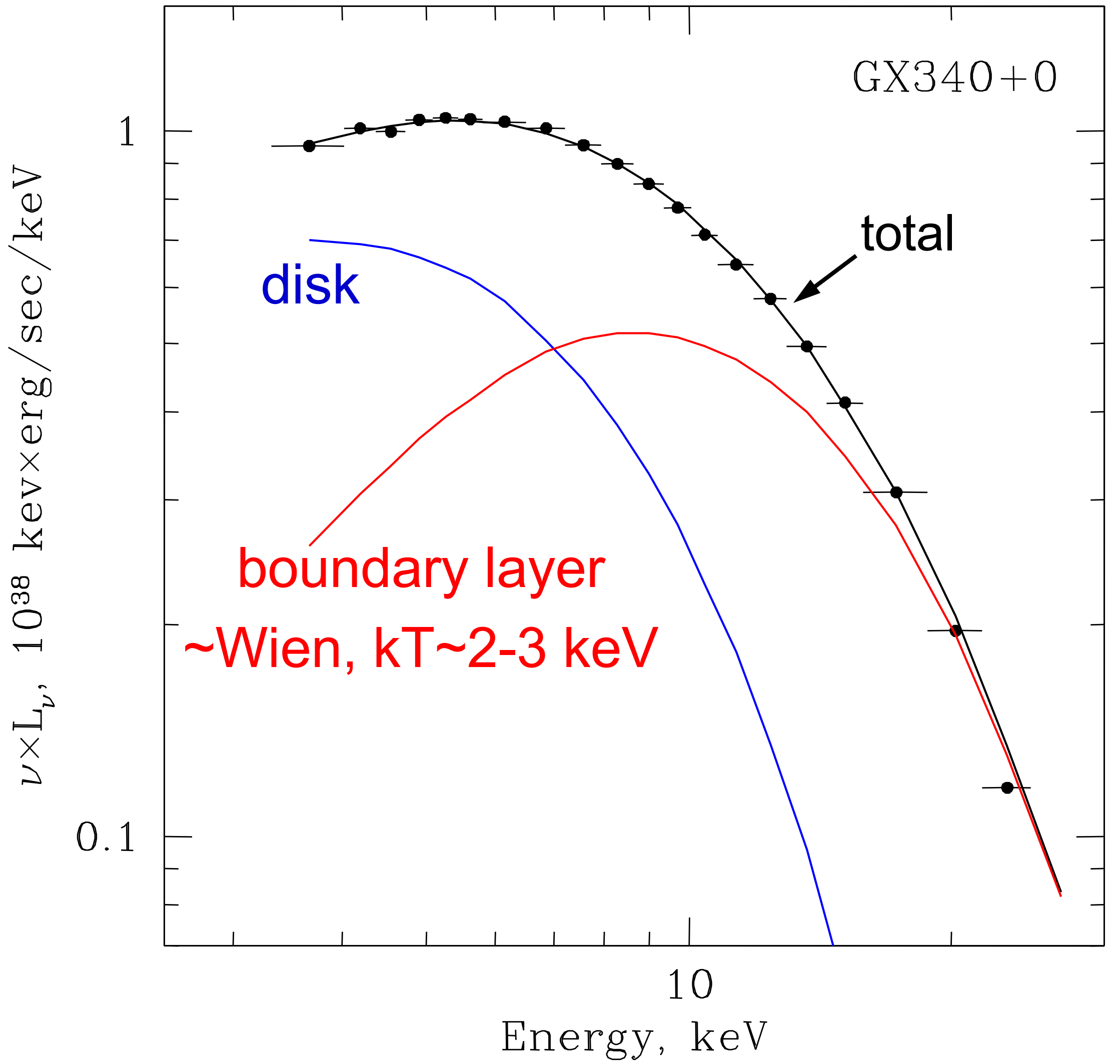
boundary layer

$$L_{tot}=L_{disk}$$

$$L_{BL}\sim L_{disk}$$

$$L_{tot}=L_{disk}+L_{BL}$$

Boundary layer and disk in NS

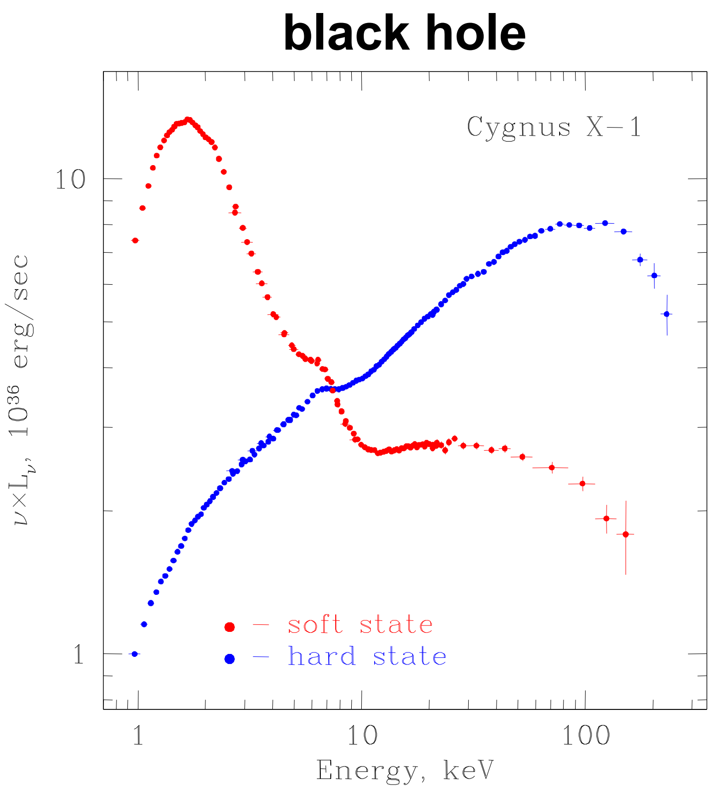


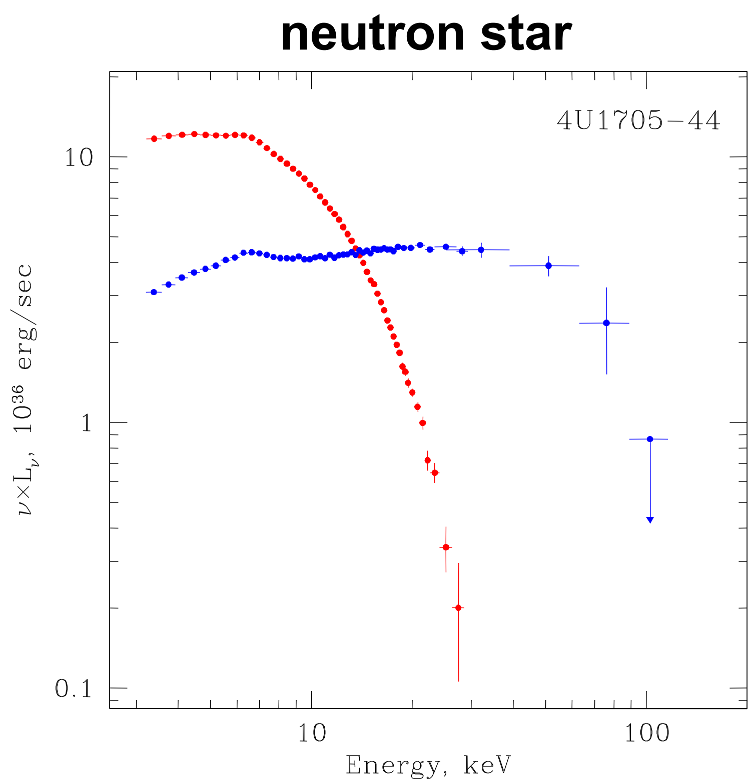
$$\dot{M} > 5 - 10\% \dot{M}_{\mathrm{Edd}}$$

Boundary layer:

- spectral component
- variability component

Spectral states: BH and NS





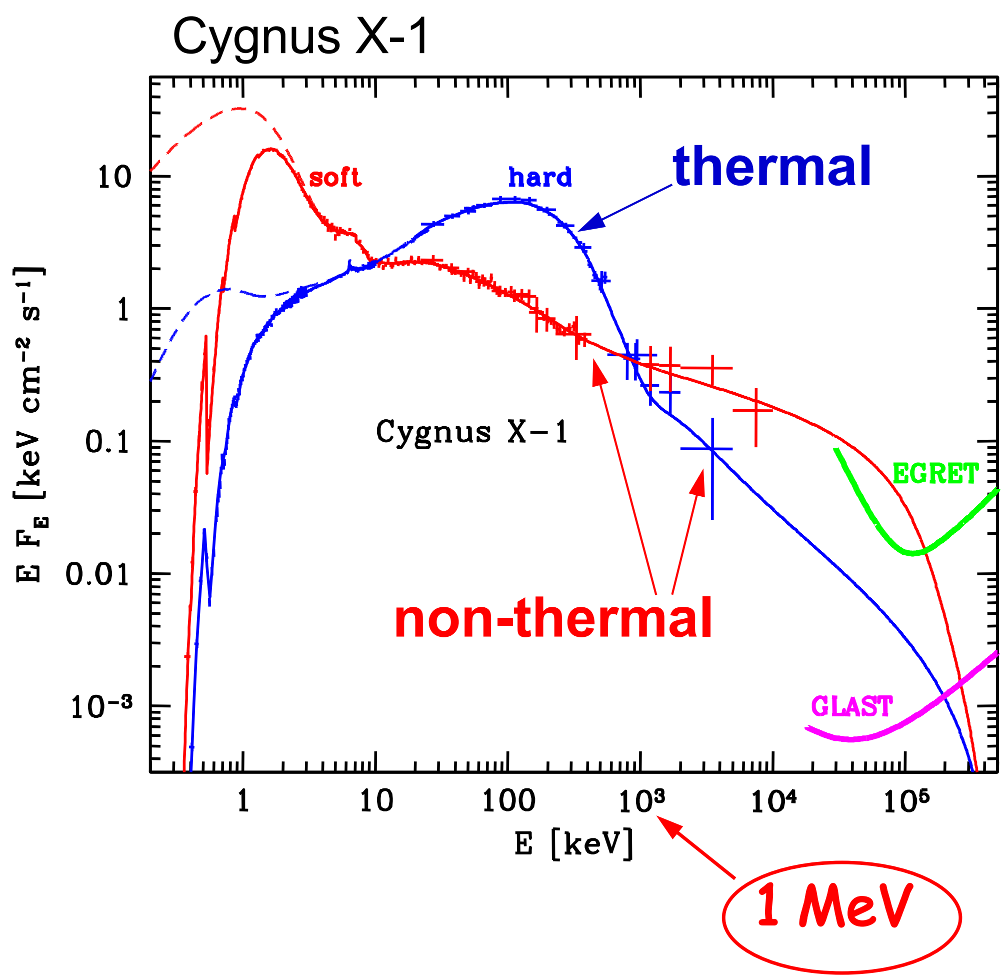
Disk: $kT_{NS} > kT_{BH}$ (difference in size + BL emission in NS)

Comptonization: $\Gamma_{NS} > \Gamma_{BH}$ $kT_{NS} < kT_{BH}$ (hard surface in NS)

$$F_E \propto E^{-(\Gamma-1)} = E^{-\alpha} \qquad \Gamma = -\frac{d\log N_E}{d\log E} = 1 - \frac{d\log F_E}{d\log E}$$

Comptonization

Comptonization: thermal & non-thermal



Poutanen & Coppi 1998; Zdziarski & Gierlinski 2004

- thermal:

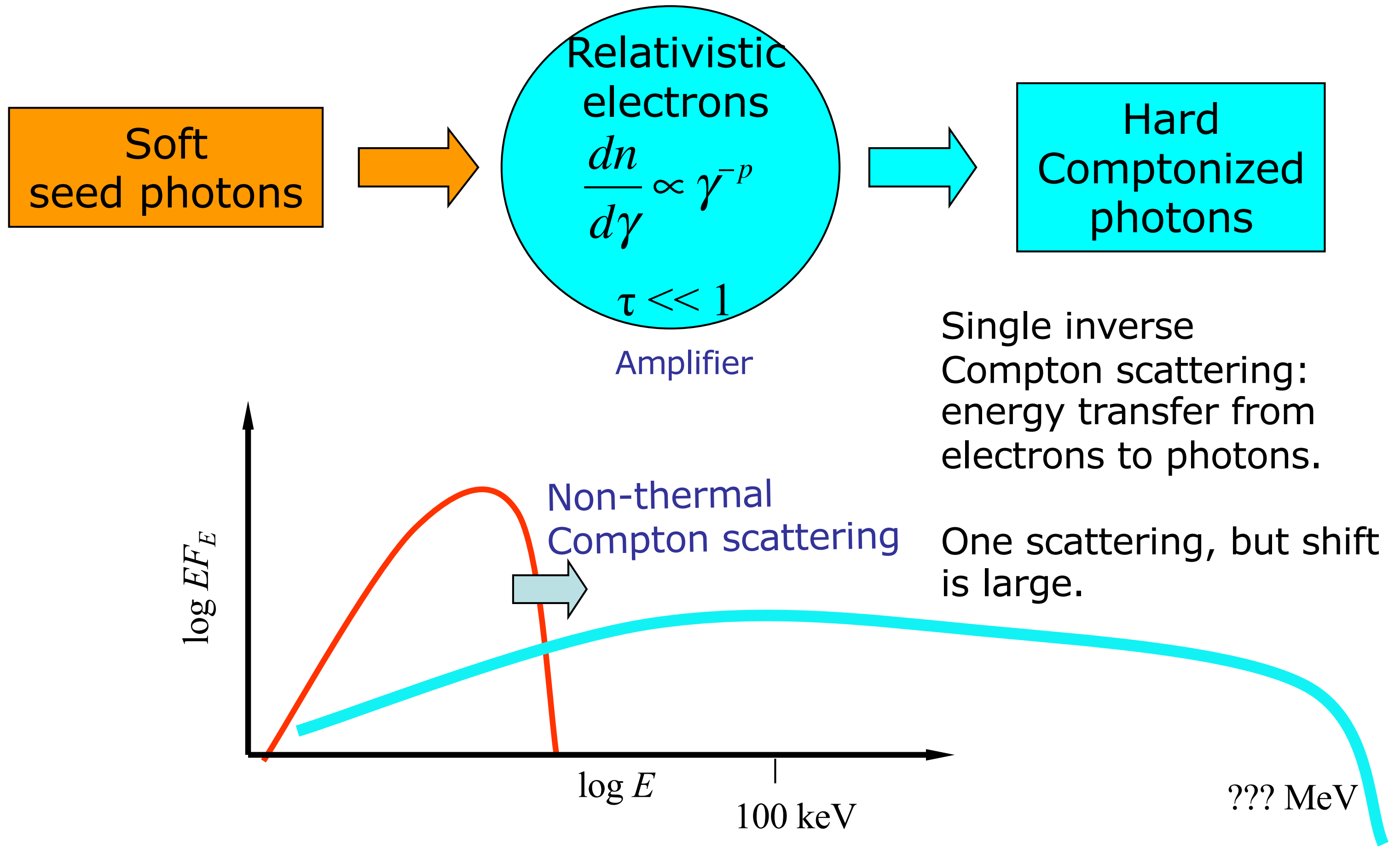
$$\frac{dN_e}{dE} \sim \text{Maxwellian}$$

- non-thermal:

$$\frac{dN_e}{dE} \propto E^{-p}$$

- soft state
  non-thermal dominates

Relativistic non-thermal plasma – (single inverse) Compton scattering



Single inverse Compton scattering: energy transfer from electrons to photons.

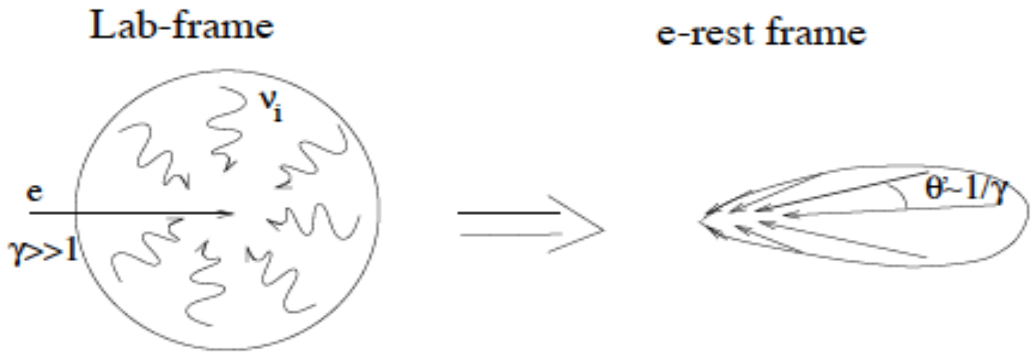
One scattering, but shift is large.

$$E' \approx E\gamma^2$$

•Inverse Compton scattering

Explanation why scattered frequency is $\nu \sim \gamma^2 \nu_i$ when $\gamma \gg 1$

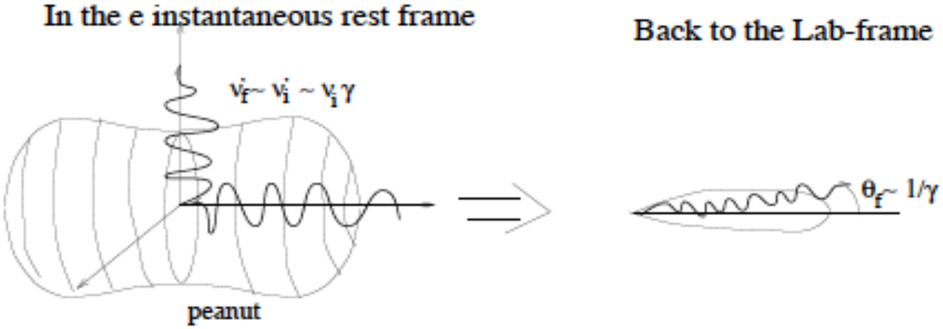
Before scattering



Isotropically incoming photons of frequency ν_i. Typical angle $\theta_i \approx \pi/2$. $\nu_i' = \nu_i \gamma(1-\beta \cos\theta_i) \approx \nu_i \gamma$. Note that we have assumed that $h\nu_i\gamma \ll m_e c^2 \rightarrow h\nu_i' \ll m_e c^2$=511 keV $\rightarrow$ Thomson scattering in the instantaneous rest frame where the electron is non-relativistic.

•Inverse Compton scattering

After scattering



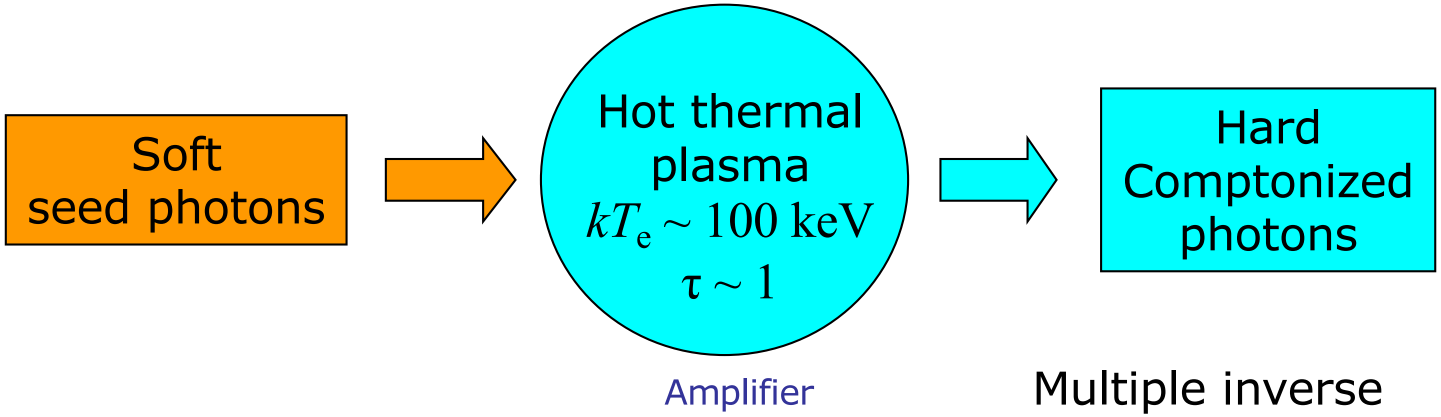
Thomson scattering: (1) in all direction, i.e. typically $\theta'_f \approx \pi/2$; (2) elastic (coherent), i.e. $\nu'_f \approx \nu'_i$. The photons are beamed in forward direction $\nu_f = \nu'_f \gamma(1 + \beta\cos\theta'_f) \approx \nu'_f\gamma \approx \nu'_i\gamma = \nu_i\gamma^2$. Exactly (neglecting recoil, $h\nu \ll m_e c^2$), relativistic Doppler effects:

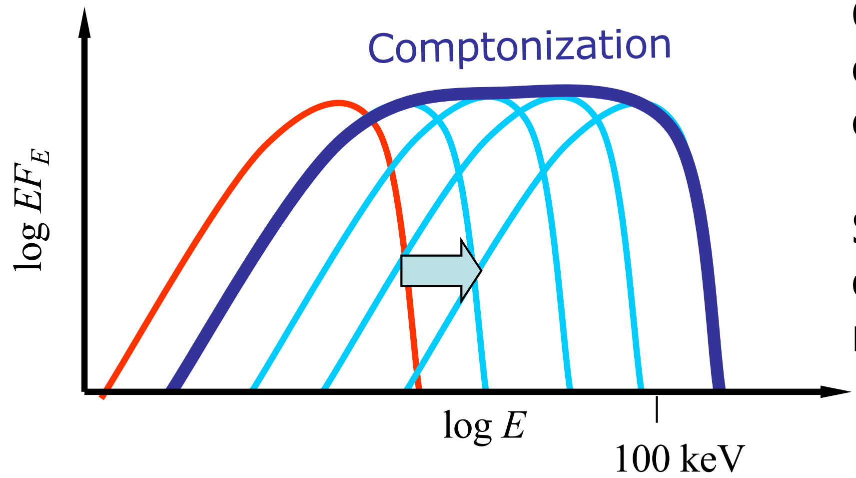
$$\nu'_i = \nu_i\gamma(1 - \beta\cos\theta_i), \quad \nu'_f = \nu_f\gamma(1 - \beta\cos\theta_f), \quad \nu'_f = \nu'_i$$

therefore

$$\nu_f = \nu_i \frac{1 - \beta\cos\theta_i}{1 - \beta\cos\theta_f}$$

Hot thermal plasma – thermal Comptonization





Multiple inverse Compton scattering: energy transfer from electrons to photons.

Small energy shift in one scattering, but many scatterings

$$\frac{\Delta E}{E} \sim \frac{E}{m_e c^2} \sim \frac{4kT_e}{m_e c^2}$$

•Inverse Compton scattering

Emitted power by an electron moving through an isotopic background of photons

Let us define the number of photons per solid angle passing through unit area in unit time $dn/d\Omega = I/(h\nu_i)$, then for isotropic radiation

$$U_{\rm rad} = \frac{1}{c}\int I\, d\Omega. \qquad \frac{dn}{d\Omega} = \frac{c}{4\pi}\frac{U_{\rm rad}}{h\nu_i}.$$

The number of interactions of the electron with the photons per unit time is

$$\frac{dN}{dt} = \sigma_T \int (1-\beta\cos\theta_i)\,\frac{dn}{d\Omega}\, d\Omega.$$

$$\boxed{\begin{aligned}\nu_f &= \nu'_f\gamma(1+\beta\cos\theta'_f)\\ \nu'_f &= \nu'_i\\ \nu'_i &= \nu_i\gamma(1-\beta\cos\theta_i)\end{aligned}}$$

$$P_{\rm Compton} = \sigma_T\langle \int (1-\beta\cos\theta_i)(h\nu_f - h\nu_i)\,\frac{dn}{d\Omega}\, d\Omega\rangle$$

$$= c\sigma_T U_{\rm rad}\langle\frac{1}{4\pi}\int[\gamma^2(1-\beta\cos\theta_i)^2(1+\beta\cos\theta'_f) - (1-\beta\cos\theta_i)]\, d\Omega\rangle,$$

$$P_{\rm Compton} = c\sigma_T U_{\rm rad}[\gamma^2(1+\beta^2/3) - 1] = \frac{4}{3}c\sigma_T U_{\rm rad}\gamma^2\beta^2 \quad \text{erg s}^{-1}.$$

•Non-relativistic Compton scattering

Non-relativistic Compton scattering

When electrons are non-relativistic, i.e. when $v \ll c$ or $kT \sim \langle mv^2/2 \rangle \ll m_e c^2$, then the energy exchange in a single scattering is very small.

This small energy exchange will be considered now in some detail. Consider the case when the electrons have more energy than the photons, $kT \gtrsim \epsilon_i$. Then the electrons lose the energy to photons. The energy loss per unit time for a nonrelativistic ($\beta \ll 1, \gamma \approx 1$) electron becomes:

$$\langle P_{Compton} \rangle = \frac{4}{3}\beta^2 c\sigma_T U_{rad} = \frac{4}{3}\beta^2 c\sigma_T n_{photon}\epsilon_i \quad \mathrm{erg\ s^{-1}}$$

where n_{photon} is the photon number density [cm^{-3}]. The number of collisions that the electron suffers per unit time is

$$\frac{dN}{dt} = c\sigma_T n_{photon} \quad \mathrm{s^{-1}}$$

•Non-relativistic Compton scattering: energy change

The mean energy loss per collision, for the electron, i.e. the mean energy gain, $\langle\Delta\epsilon\rangle$, for the photon, becomes

$$\langle\Delta\epsilon\rangle = \frac{\langle P_{Compton}\rangle}{\frac{dN}{dt}} = \frac{4}{3}\beta^2\epsilon_i$$

Consider two extreme cases:

(a) Before the collision electron and photon moving towards each other ($\theta_i = \pi$) and after the collision the photon is moving in the same direction as the electron ($\theta_f = 0$). The head-on collision gives maximal energy increase for back-scattered photons:

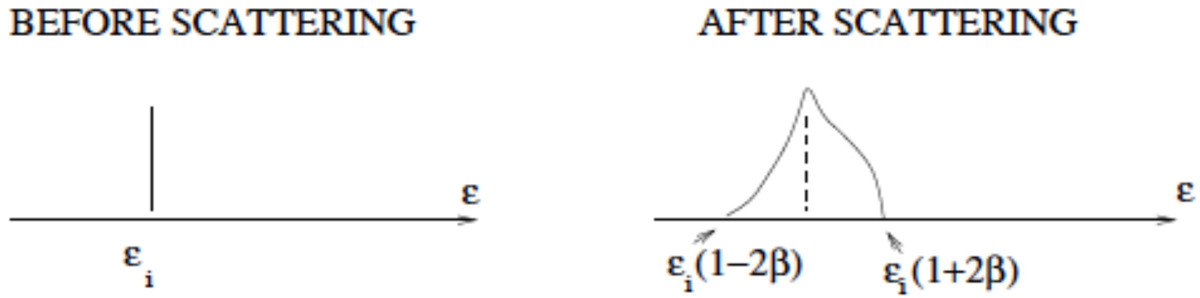
$$\epsilon_i \rightarrow \epsilon_f = \epsilon_i \left(\frac{1-\beta\cos\theta_i}{1-\beta\cos\theta_f}\right) = \epsilon_i \left(\frac{1+\beta}{1-\beta}\right) \approx \epsilon_i(1+2\beta)$$

(b) Before the collision electron and photons are moving in the same direction ($\theta_i = 0$), while after the collision in exactly opposite directions ($\theta_f = \pi$). The tail-on collision gives maximal energy decrease for back-scattered photons:

$$\epsilon_i \rightarrow \epsilon_f = \epsilon_i \left(\frac{1-\beta}{1+\beta}\right) \approx \epsilon_i(1-2\beta)$$

•Non-relativistic Compton scattering: energy change

•Head-on collisions are slightly more probable, therefore photons on average gain energy.



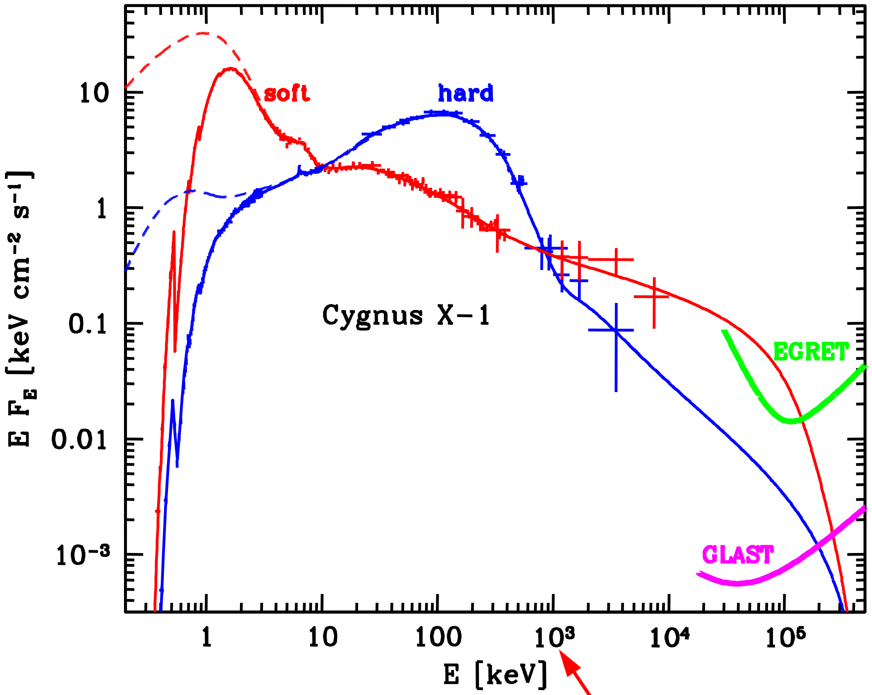
The small asymmetry (of order $O(\beta^2)$) gives mean increase

$$\langle \frac{\Delta\epsilon}{\epsilon_i} \rangle = \langle \frac{\epsilon_f - \epsilon_i}{\epsilon_i} \rangle = \frac{4}{3}\beta^2.$$

The mean over a Maxwell-Boltzmann distribution becomes

$$\langle \frac{\Delta\epsilon}{\epsilon_i} \rangle = 4\frac{kT}{m_e c^2} = 4\frac{T}{5 \times 10^9 \mathrm{K}}.$$

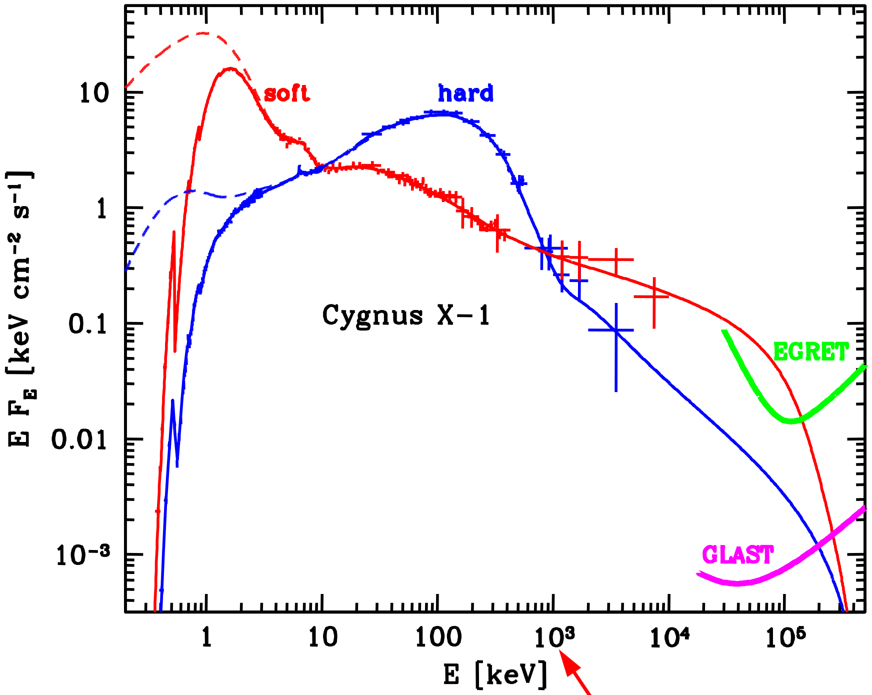
Why non-thermal Comptonization ?

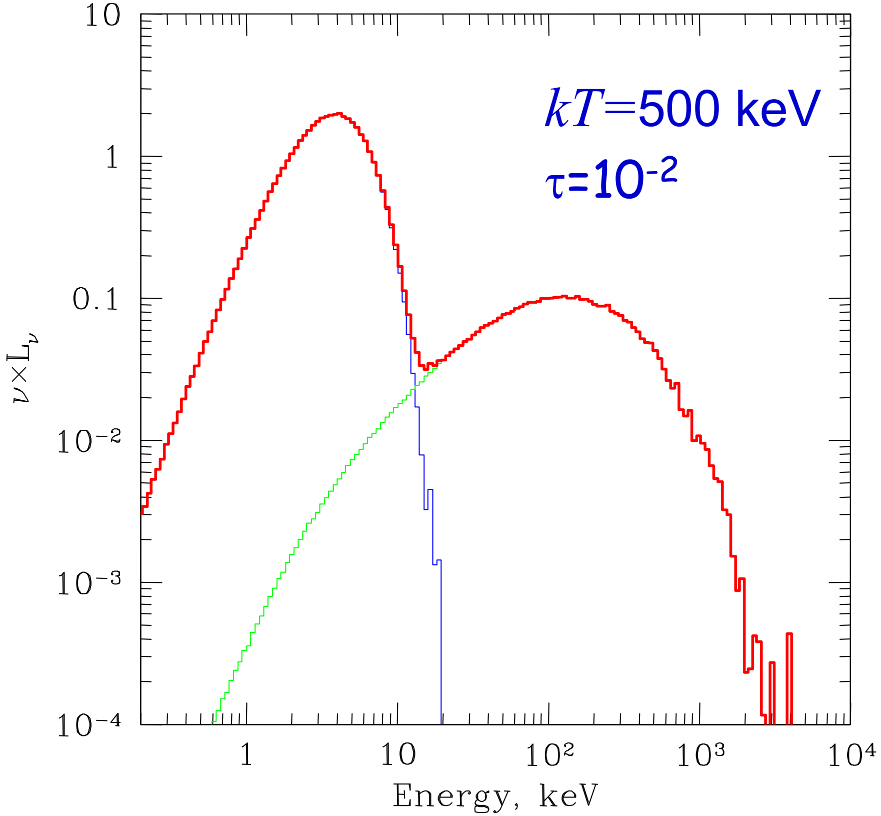


1 MeV

large kT_e, small τ are required

Why non-thermal Comptonization ?



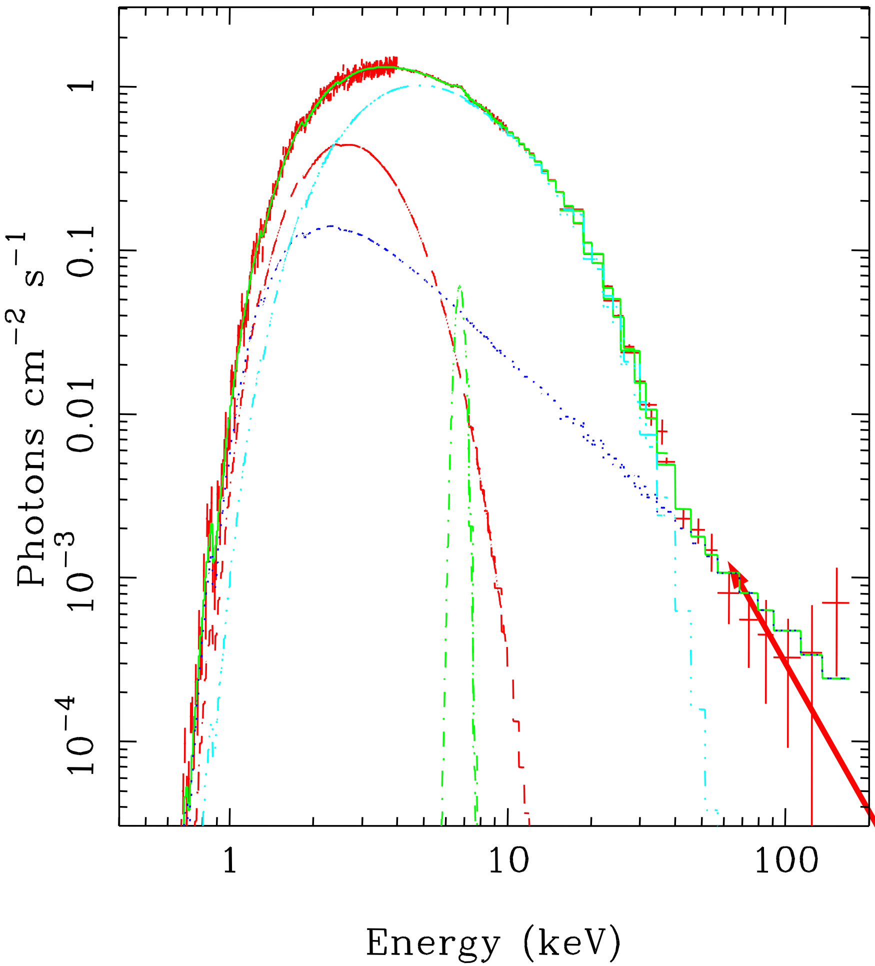


1 MeV

large kT_e, small τ are required

Neutron stars

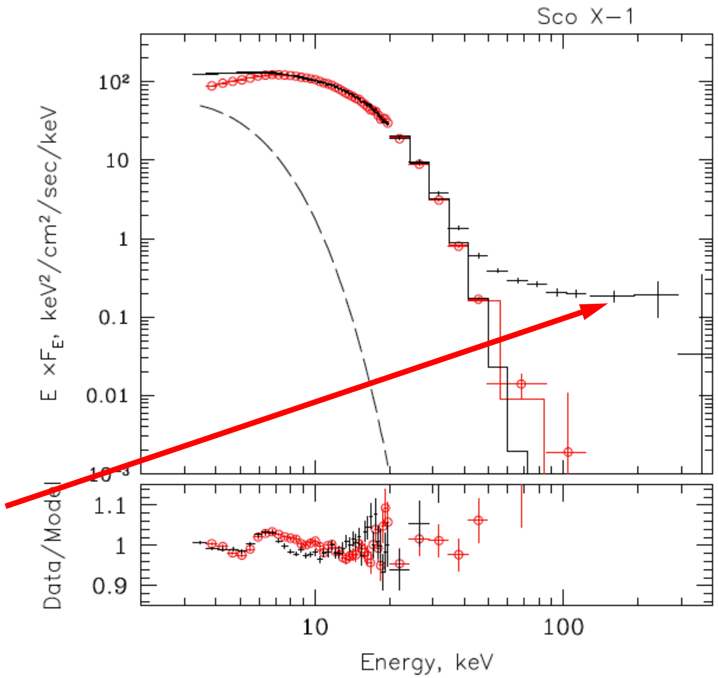
GX 17+2



from Di Salvo et al., 2000

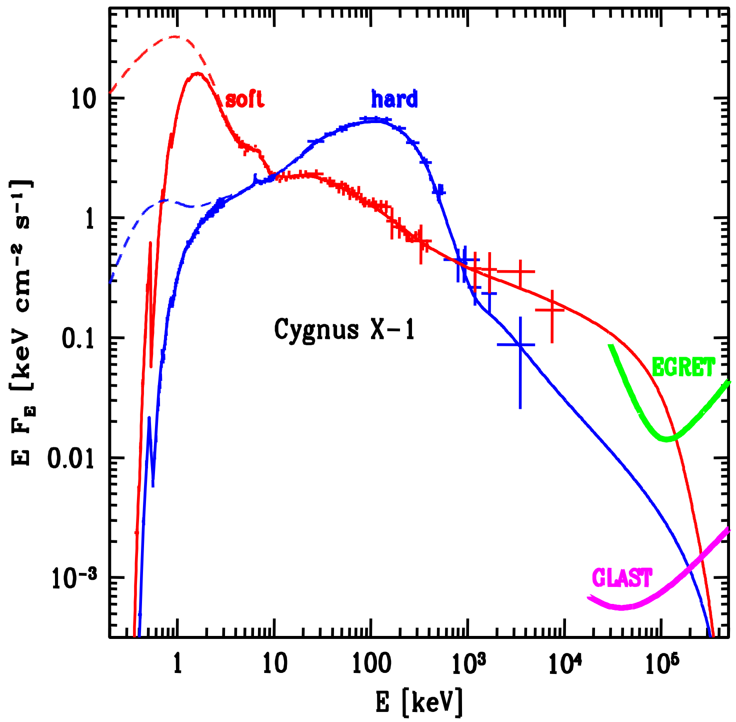
- nature of the high energy tail is unclear
- energetically unimportant

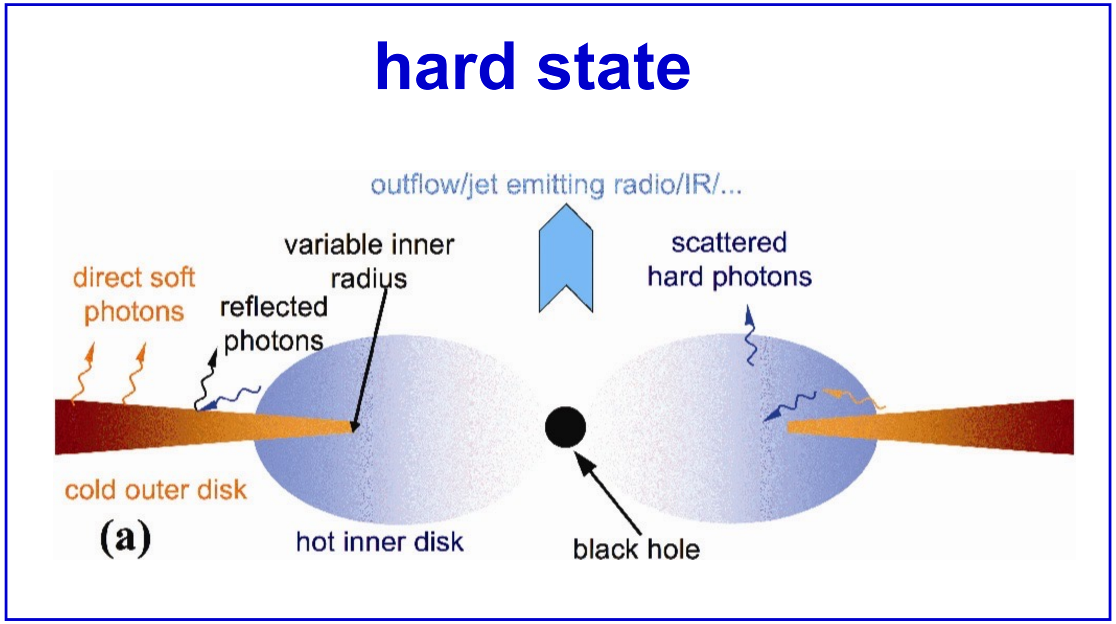
???

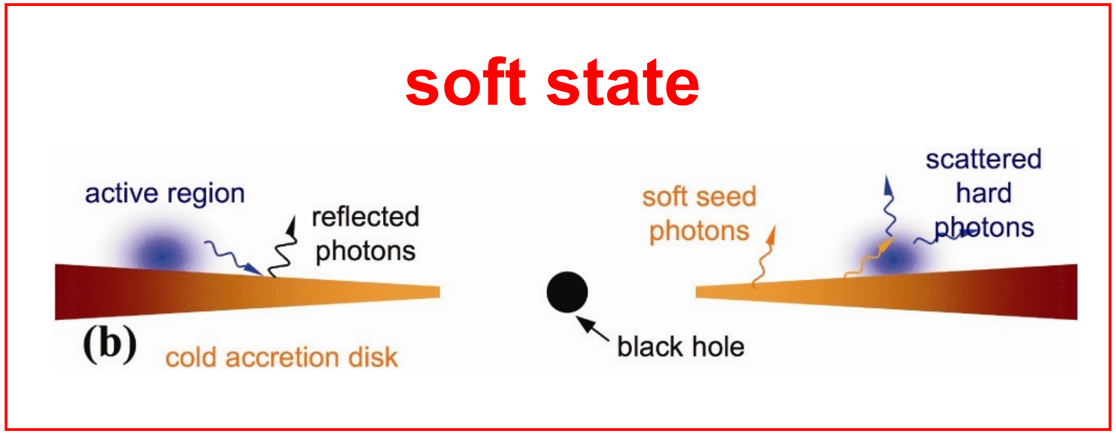


Revnivtsev et al. 2014

Geometry

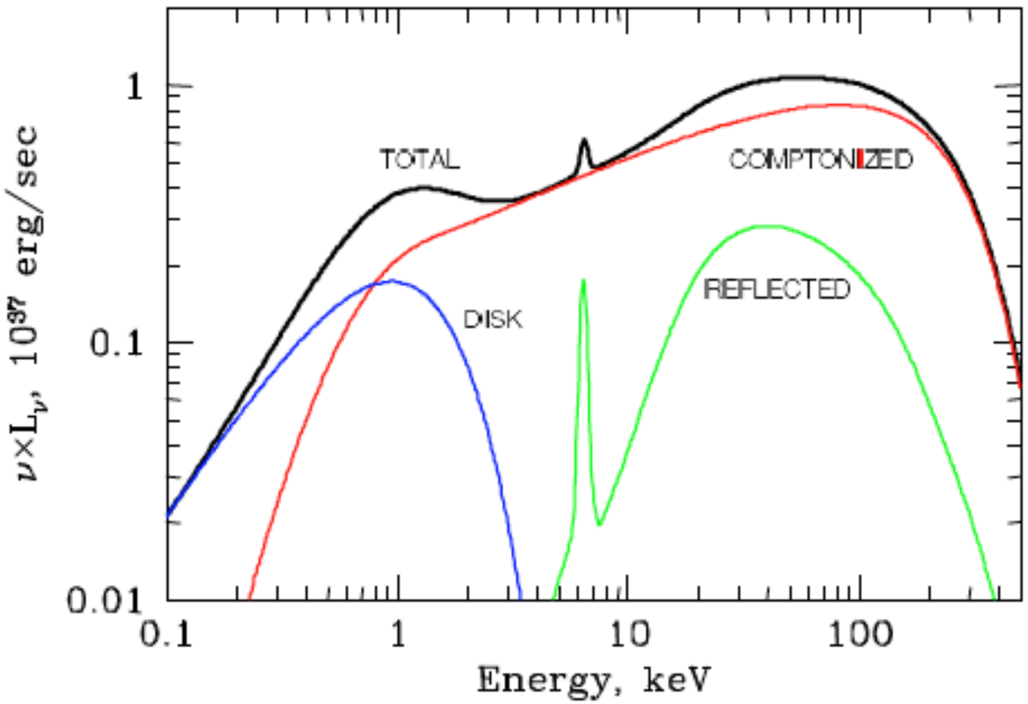






- Hard state - standard cold outer disk + hot inner flow?
- Soft state - standard accretion α -disk, plus corona?

Spectrum and geometry
(hard state)



$F_{\rm compt} \sim 90\%\ F_{\rm tot}$

$kT_{\rm disk} \sim 150$ eV